FERMILAB-Proposal-0496

A NEUTRINO DETECTOR SENSITIVE TO RARE PROCESSES

I. A STUDY OF NEUTRINO ELECTRON REACTIONS

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ABSTRACT

We propose to construct a new counter system to study rare neutrino processes which are a factor of 10^3-10^4 smaller than the usual charged current reaction. The first use of this detector will be to study neutrino electron reactions, in particular, the study of ν_μ, e^- elastic scattering and ν_μ, e^- inverse muon decay. The key feature of this detector system is a totally live target/calorimeter section which contains roughly a thousand independent thin sampling layers. Analog information from these layers are used to:

i) identify single charge particle recoil events,

ii) limit excess energy deposition at the interaction vertex,

iii) separate electromagnetic from hadronic cascades, and

iv) measure the energy of the single particle.

With these capabilities, this detector system will be able to select ν_μ, e^- elastic scattering, and ν_μ, e^- inverse muon decay events from the more copious ν_μ reactions.

For the study of ν_μ, e^- elastic scattering and ν_μ, e^- inverse muon decay, we require the wide band ν_μ beam with 1 ms spill, and 1 Coulomb of 400 GeV protons i.e. 10^{13} pps, 600 pulses/hr, and 1000 hrs. With such an exposure, and an 80 ton fiducial target we expect to collect roughly 200 ν_μ, e^- elastic scattering events assuming the minimum Weinberg/Salam-Ward cross section and roughly 1,200 ν_μ, e^- inverse muon decay events.

Absolute normalization with the wide band ν_μ beam flux and spectrum would be via the quasi-elastic reaction $\nu_\mu\, n \rightarrow p\, \mu^-$. We intend to measure the absolute cross section for this reaction at an early date in a run using the dichromatic beam and a prototype section of the target/calorimeter. Exposure of this prototype to the wide band ν_μ beam may result in early observation of the ν_μ, e^- elastic scattering reaction.

Future experiments which follow naturally for this detector, possibly with the energy doubler, include the remaining neutrino electron reactions, i.e.

i) a study of $\bar{\nu}_\mu, e^-$ elastic scattering,

ii) a test of the multiplicative lepton number conservation law via a search for $\bar{\nu}_\mu\, e^- \rightarrow \bar{\nu}_e\, \mu^-$, and

iii) a study of ν_e ($\bar{\nu}_e$), e^- elastic scattering.

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I. Introduction

Neutrino electron (four Fermion leptonic) reactions are fundamental reactions in weak interaction theories. The existence of such reactions, e.g. ν_e, e^- elastic scattering, ν_μ, e^- elastic scattering, and ν_μ, e^- inverse muon decay, has been expected theoretically for some time.[1,2,3,4] However, the experimental study of such reactions has been exceedingly difficult. The basic difficulty rests with the relatively nondescript nature of the reaction, i.e. a single recoil electron or muon, and with miniscule expected cross sections, thus event rates, relative to the many varieties of backgrounds.

At Fermilab energies, neutrino electron cross sections are smaller than neutrino nucleon cross sections by a factor in the range 10^3 - 10^4. The neutrino nucleon reactions are now being studied at Fermilab by both counter and bubble chamber experiments. These experiments have had remarkable success, culminating so far, in the discovery of dilepton ($\mu\mu$ and μe) events[5,6,7] which have an observed rate roughly 1% of the usual charge current rate. With recent modifications directed towards improving the study of neutrino nucleon reactions, the counter detector systems have an adequate mass, but lack the required selectivity for the study of neutrino electron reactions. Alternately, the bubble chamber may have the required selectivity, but lacks adequate mass for this study. In addition to neutrino electron reactions many new phenomena, which may exist at the level of 10^{-3} - 10^{-4} that of the usual charged current rate, are not within the capability of these existing neutrino detector systems.

We propose to build a new counter neutrino detector at approximately the same mass scale as the existing neutrino counter experiments, i.e. approximately 100 tons target mass, but which would have the necessary selectivity to study rare processes at the level of 10^{-3}-10^{-4} that of the usual charged current cross section. We focus here on the study of neutrino electron reactions since it presents a definite goal with expected cross sections of the appropriate magnitude. This new counter experiment will require a new target/calorimeter and it will also incorporate the Caltech/Fermilab neutrino detector.

In order to achieve the required selectivity, our detector design focuses upon the nondescript nature of neutrino electron reactions, i.e. the single recoil electron or muon. Our approach is unique in that we use a highly segmented live target/calorimeter with <u>independent</u> sampling for each layer (Section V, detector system). The independent sampling for each layer effectively provides a multiplicity of dE/dx measurements. Such measurements near the event vertex can place a severe limit on ν (the hadron energy) in neutrino nucleon reactions. We intend to use the analog information from these layers to

i) identify single charged particle recoil events,

ii) limit excess energy deposition at the interaction vertex,

iii) separate electromagnetic from hadronic cascades, and

iv) measure the energy of the particle.

Such capabilities can isolate neutrino electron events from the more copious neutrino nucleon events. (Section IV, background discrimination method).

For the study of ν_μ, e^- elastic scattering and ν_μ, e^- inverse muon decay, we require the wide band ν_μ beam with 1 ms spill and 1 Coulomb of 400 GeV protons, i.e. 10^{13} pps, 600 pulses/hr and 1000 hrs. With such an exposure, and an 80 ton fiducial target, we expect to collect roughly 200 ν_μ, e^- elastic scattering events, assuming the minimum Weinberg/Salam-Ward cross section at $x = 0.375$, and roughly 1200 ν_μ, e^- inverse muon decay events (Section VI, Event rates).

Absolute normalization for the wide band ν_μ beam flux and spectrum would be via the quasi-elastic reaction $\nu_\mu\, n \to p\, \mu^-$. We intend to measure the absolute cross section for this reaction at an early date in a run using the dichromatic beam and a prototype section of the target/calorimeter. (Section III, proposed schedule). The prototype will be installed in place of the first section of the hadron calorimeter in the Caltech/Fermilab detector, and would have approximately an 8 ton fiducial target. Exposure of this prototype to the wide band ν_μ beam could result in early observation of the ν_μ, e^- elastic scattering reaction.

Future experiments for this detector, possibly with the energy doubler, include the remaining neutrino electron reactions, i.e.

1) a study of $\bar{\nu}_\mu$, e^- elastic scattering
2) a test of the multiplicative lepton number conservation law via a search for $\bar{\nu}_\mu\, e^- \to \bar{\nu}_e\, \mu^-$, and
3) a study of $\nu_e(\bar{\nu}_e)$, e^- elastic scattering.

These would require respectively, the wide band $\bar{\nu}_\mu$ beam and the proposed K° decay neutrino beam.

$\nu_\mu e^- \to \mu^- \nu_e$

II. Physics Motivation

The neutrino electron elastic scattering reactions,

$$\nu_e \, e^- \to \nu_e \, e^- \tag{1}$$

$$\bar{\nu}_e \, e^- \to \bar{\nu}_e \, e^- \tag{1'}$$

$$\nu_\mu \, e^- \to \nu_\mu \, e^- \tag{2}$$

$$\bar{\nu}_\mu \, e^- \to \bar{\nu}_\mu \, e^- \tag{2'}$$

are fundamental reactions in weak interaction theories. Reaction (1) [(1')] is an example of a "diagonal" interaction[1] which has a contribution from the usual charge currents of universal V-A theory,[2] and which may also have a contribution from neutral currents of gauge theories.[3,4] Reaction (2) [(2')] is an example which has only the neutral current contribution. The study of neutrino electron (purely leptonic) reactions, due to the simplicity of the interacting particles, provides a stringent testing ground for basic theoretical ideas without complications arising from hadronic structure. Therefore, it is important to study these reactions.

These reactions have been searched for at reactors in the MeV range ($\sim$ 4 MeV) with $\bar{\nu}_e$'s, and at accelerators in the GeV range ($\sim$ 1 GeV) with ν_μ's and $\bar{\nu}_\mu$'s. The status at the SRP reactor[8] for $\bar{\nu}_e$, e^- elastic scattering was,

$$\frac{\sigma_{expt}}{\sigma_{V-A}} = 1.5 \pm 0.70.$$

The observation of this reaction has been reported recently.[9] At CERN, three candidates for reaction (2) have been found in Gargamelle,[10] the heavy liquid bubble chamber. Other experiments, both at

CERN[11] and at BNL,[12] which are directed at reaction (2), are in progress. There have also been approved proposals at LAMPF,[13] as well as Fermilab[14] to search for reactions (1) and/or (2). A multiplicity of other proposals also exist.[15] The variety of attempts and methods gives a rough measure of the difficulty of neutrino electron elastic scattering experiments.

The neutrino electron inverse muon decay reactions,

$$\nu_\mu \, e^- \rightarrow \nu_e \, \mu^- \tag{3}$$

$$\bar{\nu}_e \, e^- \rightarrow \bar{\nu}_\mu \, \mu^-, \tag{3'}$$

are also basic to weak interaction theories. The usual theory assumes separate additive lepton number conservation of the electron type and of the muon type. The inverse reaction, in contrast to muon decay, is particularly sensitive to deviations from V-A theory,[16] i.e. $g_A \neq g_V$. The best determination of the ratio, $|g_A/g_V|$, so far comes from a measurement of the η parameter which characterizes the low energy end of the electron spectrum in muon decay. The result[17] is $|g_A/g_V| = 0.86 \begin{smallmatrix} +\,0.33 \\ -\,0.11 \end{smallmatrix}$, i.e. V-A holds to roughly 25%. Thus the cross section for reaction (3) may deviate from the V-A prediction by roughly 25%.

The following inverse muon decay reactions,

$$\bar{\nu}_\mu \, e^- \rightarrow \bar{\nu}_e \, \mu^- \tag{4}$$

$$\nu_e \, e^- \rightarrow \nu_\mu \, \mu^-, \tag{4'}$$

are prohibited by the additive lepton number conservation law, but they are allowed by the multiplicative lepton number conservation law.[18] A search for either reaction would test the additive law of lepton number conservation.

A limit on r, the ratio of the multiplicative law decay rate to the total decay rate of the muon, has been set at CERN by Gargamelle using neutrinos from muon decay.[19] The maximal value of r is 0.5, and the Gargamelle limit is 0.25. An approved experiment at LAMPF, to test the multiplicative law by searching for $\bar{\nu}_e$'s in μ^+ decay at rest, is in its initial stages.[20] Other tests of the multiplicative lepton number conservation law exist e.g. searches for $\mu^+ e^- \to \mu^- e^+$,[21] but the sensitivity of such tests are not yet anticipated to be at the level of the Fermi coupling constant.

III. Proposed Schedule

Recognizing the difficulties associated with the study of neutrino electron reactions, we concluded that an intermediate step, on a scale smaller than our proposed 100 tons, would be useful. Such a step should be relatively modest and would be used to demonstrate the detector capability. Due to the modular nature of our approach this appears possible. Furthermore, we believe that interesting physics can be done with this relatively modest detector. Therefore, we are proposing to proceed in two stages.

1. Stage I

For stage I, we intend to install a prototype of the live target/calorimeter in place of the first hadron calorimeter section in the Caltech/Fermilab detector. This is shown in Fig. 1. The prototype would have a total target mass of about 15 tons and a fiducial target mass of about 8 tons. The prototype will be run in conjunction with the Caltech/Fermilab detector, which is scheduled to receive neutrinos from the dichromatic beam. We anticipate that this prototype can be ready roughly 18 months after approval of this experiment.

The physics goal in stage 1 would be twofold: (1) To initiate studies with this sensitive new detector for undiscovered phenomena and (2) to measure the absolute cross section of the quasi-elastic reaction, $\nu_\mu n \rightarrow p \mu^-$.

PROPOSED STAGE I DETECTOR

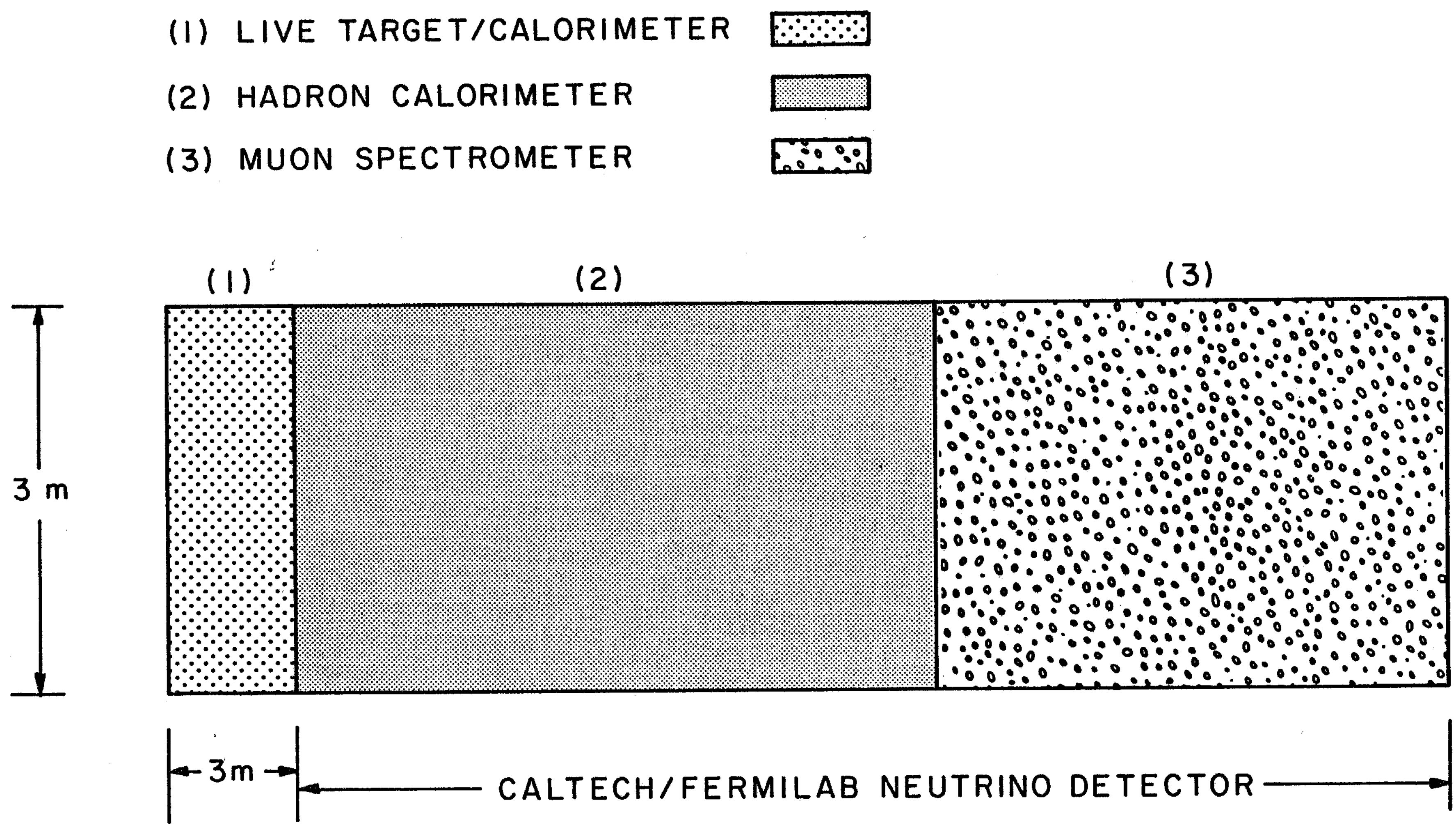

Fig. 1

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The constancy of quasi-elastic neutrino nucleon cross sections at neutrino energies greater than several GeV has not been established experimentally. Furthermore the magnitude of these cross sections are completely undetermined by experiments. Earlier measurements were carried out at much lower neutrino energies[22]. Knowledge of these cross sections are also important for normalization in any neutrino experiment using the wide band beam. We anticipate that the dichromatic beam with 1 Coulomb of 400 GeV protons will give between 500 and 1000 $\nu_\mu\, n \rightarrow p\, \mu^-$ interactions in the prototype detector. Such an exposure would provide ample opportunity for the demonstration of its discrimination capabilities. e.g. The expected sensitivity to very low ν and very low q^2 which is unique to our target/calorimeter will be used to separate the quasi-elastic reaction, $\nu_\mu\, n \rightarrow p\, \mu^-$ from other neutrino reactions involving pion production. As suggested earlier, this type of capability has significant implications beyond our present goal of studying neutrino electron reactions, but these will not be addressed here.

Assuming that this demonstration is carried out successfully, we estimate that a comparable exposure of this prototype to the wide band ν_μ beam will result in a collection of about 20 ν_μ, e^- elastic scattering events. Thus, the ν_μ, e^- elastic scattering reaction might be observed at an early date.

2. <u>Stage II</u>

For stage II, we are contemplating the configuration shown in Fig. 2. This leaves the entire Caltech/Fermilab detector essentially intact by locating the 100 ton live target/calorimeter in a frontal

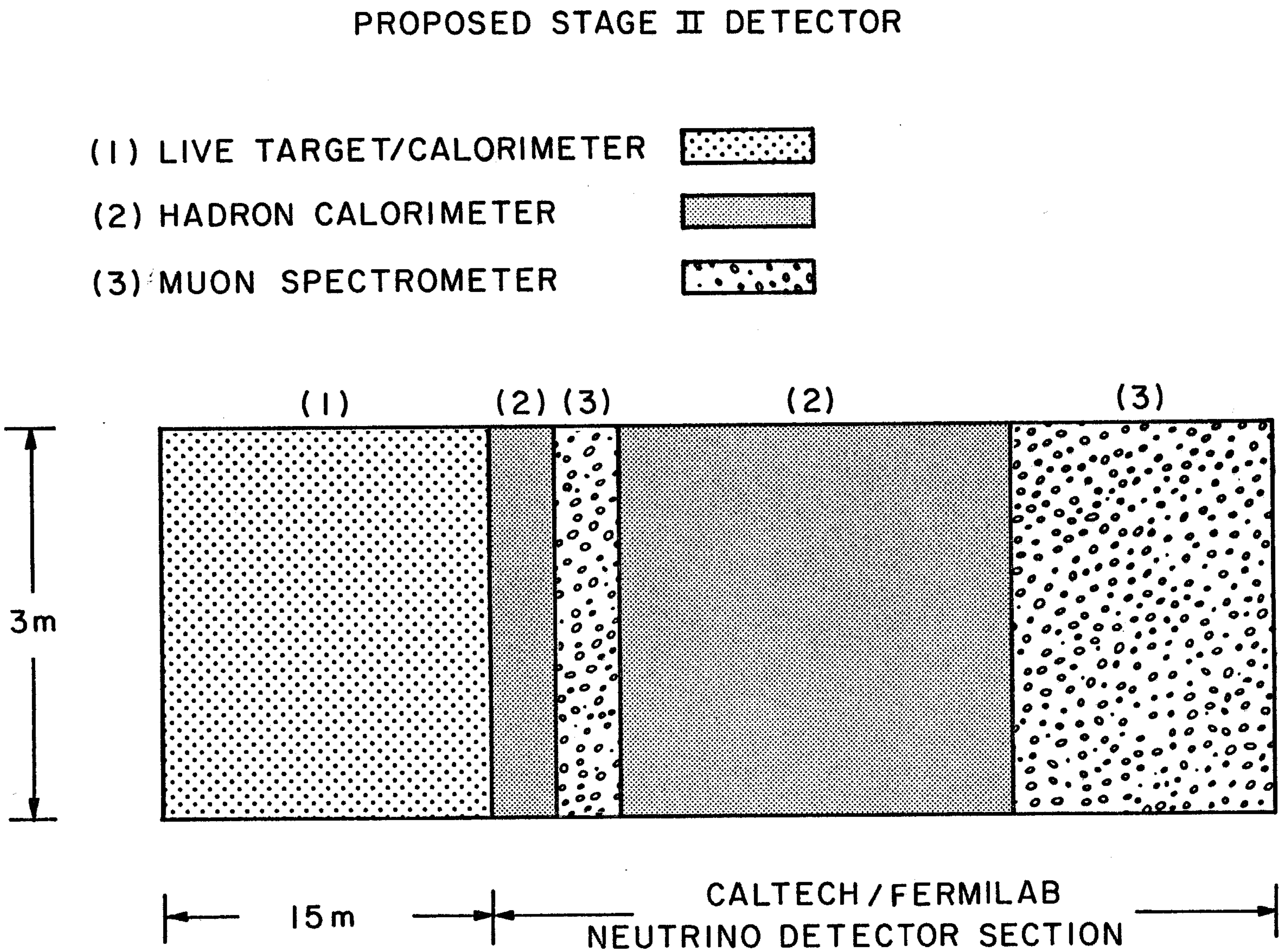
PROPOSED STAGE II DETECTOR
(1) LIVE TARGET/CALORIMETER
(2) HADRON CALORIMETER
(3) MUON SPECTROMETER
(1)
(2)
(3)
(2)
(3)
3m
15m
CALTECH/FERMILAB
NEUTRINO DETECTOR SECTION

Fig. 2

496(8A)

extension of Lab. E. Such a configuration allows great flexibility with minimal sacrifice of neutrino electron events. This is possible since recoil angles in neutrino electron reactions are small. This particular geometry also minimizes interference with the overall Fermilab neutrino program, i.e. while installing the new target/calorimeter, the Caltech/Fermilab detector can continue to be used.

IV. Background Discrimination Method

The key method, used so far in the separation of ν, e elastic scattering events from background, has been the electron angular distribution. A major background for ν,e elastic scattering comes from the quasi-elastic inverse beta reaction,

$$\nu_e \; n \rightarrow p \; e^- \tag{5}$$

At neutrino energies less than a few GeV, electrons from reaction (5) are essentially isotropic, whereas electrons from ν,e elastic scattering are focused in a forward cone, with $\theta_e \leqslant \sqrt{2m_e/E_\nu}$. Thus angular distributions can be used to discriminate against the inverse beta reaction. Discrimination factors $\geqslant 30$ are achieved with neutrino energies in the range $\leqslant 1$ GeV. At higher neutrino energies, i.e. FNAL and SPS, the angular discrimination factor becomes progressively less favorable.

With neutrino energies much larger than the nucleon mass, two effects force electrons from reaction (5) to peak in the forward cone, i.e. relativistic kinematics and "weak" nucleon form factors. The combination is such that the forward cone for reaction (5) decreases rapidly. The kinematics for reaction (5) is shown in the solid curves of Fig. 3. The recoil proton kinetic energy is given as a function of the electron angle. Since weak nucleon form factors cut off inverse beta cross sections at $|q^2| \sim m_p^2$, this implies that the mean recoil proton kinetic energy, $\overline{T}_p$, is ~ 250 MeV. The consequence is that electrons from reaction (5) are peaked within ~ 70, 35, 17, and 7 mr for incident neutrino energies of 10, 20, 40 and 100 GeV, respectively.

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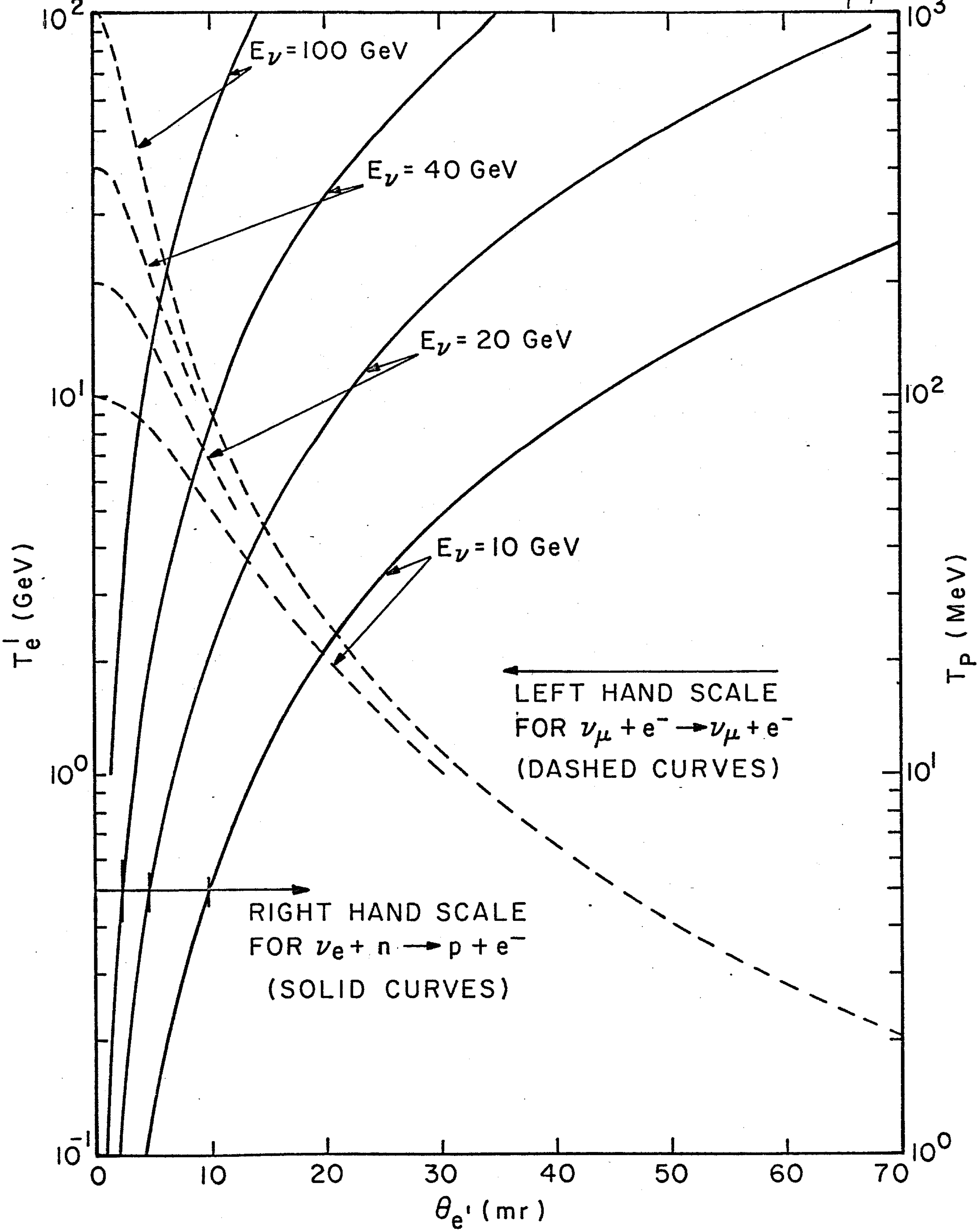

E_ν = 100 GeV
E_ν = 40 GeV
E_ν = 20 GeV
E_ν = 10 GeV
LEFT HAND SCALE
FOR $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$
(DASHED CURVES)
RIGHT HAND SCALE
FOR $\nu_e + n \rightarrow p + e^-$
(SOLID CURVES)
T_e' (GeV)
T_P (MeV)
$\theta_{e'}$ (mr)
10^2
10^1
10^0
10^{-1}
10^3
10^2
10^1
10^0
0
10
20
30
40
50
60
70

Fig. 3

The corresponding recoil electron cone angle for ν,e elastic scattering at these energies are 10, 7, 5, and 3 mr ($\theta_e = \sqrt{2m_e/E_\nu}$). Thus the electron angle cut becomes progressively less useful at higher energies.

A severe limitation of the electron angle cut is that a significant fraction of the ν,e elastic scattering differential cross section is lost. In particular, the $\theta_e \leqslant \sqrt{2m_e/E_\nu}$ cut is equivalent to removing, in the center of mass frame (CM), ν,e elastic scattering events which are in the forward hemisphere. In order to decrease the loss cone in the CM, one has to accept electrons at larger (lab) angles, e.g. in order to accept 90% of the CM solid angle, the electron (lab) angle cut has to be increased by a factor of 3. From Fig. 3, it is clear that this relaxation cannot be tolerated.

These observations indicate that the forward peaking of recoil electrons in ν,e elastic scattering becomes progressively less distinct at higher incident neutrino energies. Furthermore, its application is not attractive since it eliminates a large fraction of the ν,e elastic scattering CM solid angle from experimental study.

A better alternative to the above is the use of transverse momentum. A fixed transverse momentum cut can be chosen so as to minimize its effect on ν,e elastic scattering. Fig. 4 shows the corresponding kinematics as a function of the transverse momentum, $p_\perp$. As before, the separation between ν,e elastic scattering and inverse beta progressively decreases at higher

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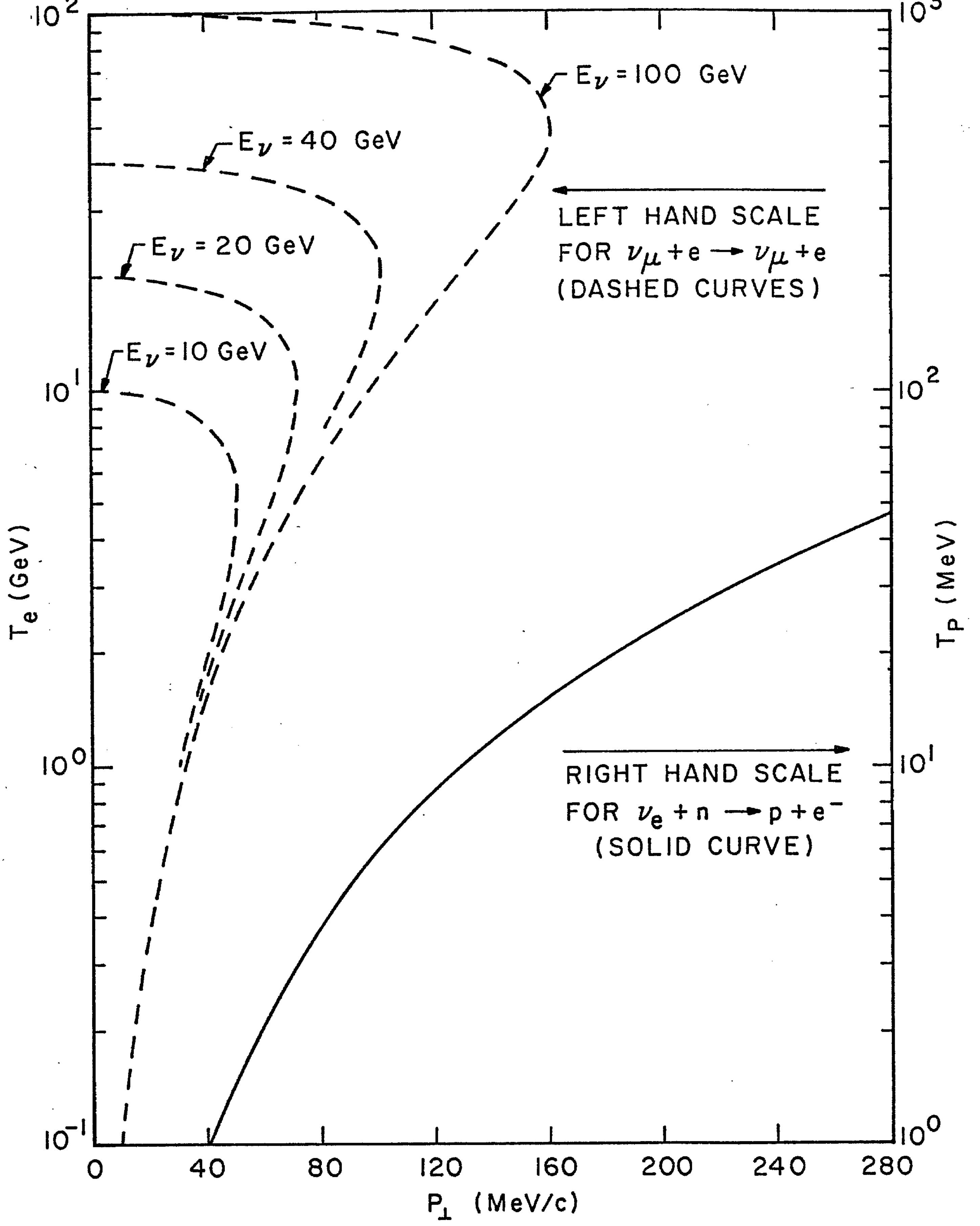

$E_\nu = 100$ GeV
$E_\nu = 40$ GeV
$E_\nu = 20$ GeV
$E_\nu = 10$ GeV
LEFT HAND SCALE
FOR $\nu_\mu + e \rightarrow \nu_\mu + e$
(DASHED CURVES)
RIGHT HAND SCALE
FOR $\nu_e + n \rightarrow p + e^-$
(SOLID CURVE)
T_e (GeV)
T_P (MeV)
$P_\perp$ (MeV/c)
10^2
10^1
10^0
10^{-1}
10^3
10^2
10^1
10^0
0
40
80
120
160
200
240
280

Fig. 4

incident neutrino energies. However, at present energies, i.e. $E_\nu \sim 20$ GeV, the separation is reasonably good. e.g. A cut at $p_\perp \sim 100$ MeV/c leaves roughly 4% of the inverse beta spectrum. At higher energies, e.g. $E_\nu \sim 50$ GeV (with the energy doubler at FNAL), the corresponding $p_\perp$ cut would be 160 MeV/c. Such a cut would leave about 10% of the inverse beta spectrum. This loss of discrimination at higher energy is offset by the linear growth of the ν,e elastic scattering cross section relative to the constant cross section for reaction (5). Therefore, with this approach, ν,e elastic scattering remains relatively unaffected, i.e. there is no significant modification of the signal to background ratio at higher neutrino energies.

Potentially the best method to separate ν,e elastic scattering events from inverse beta events is to limit "activity" at the interaction vertex. If the recoil proton in reaction (5) could be detected down to a few MeV, one would have a simple criteria which does not bias ν,e elastic scattering. Fig. 3 shows, for example, that a 2 MeV limit on T_p, the recoil proton kinetic energy, would be equivalent to an electron angle cut of 6, 3, $1\frac{1}{2}$, and 0.6 mr at incident neutrino energies of 10, 20, 40 and 100 GeV, respectively. Fig. 4 shows that the 2 MeV limit on T_p would be equivalent to limiting $p_\perp$ to roughly 60 MeV/c. Since excess energy deposition at the vertex is associated with reaction (5), there is neither a loss of elastic scattering events nor a loss of discrimination capability at higher neutrino energies. In fact, the signal to background ratio would improve at higher neutrino energies with the linear growth of the ν,e elastic scattering cross section.

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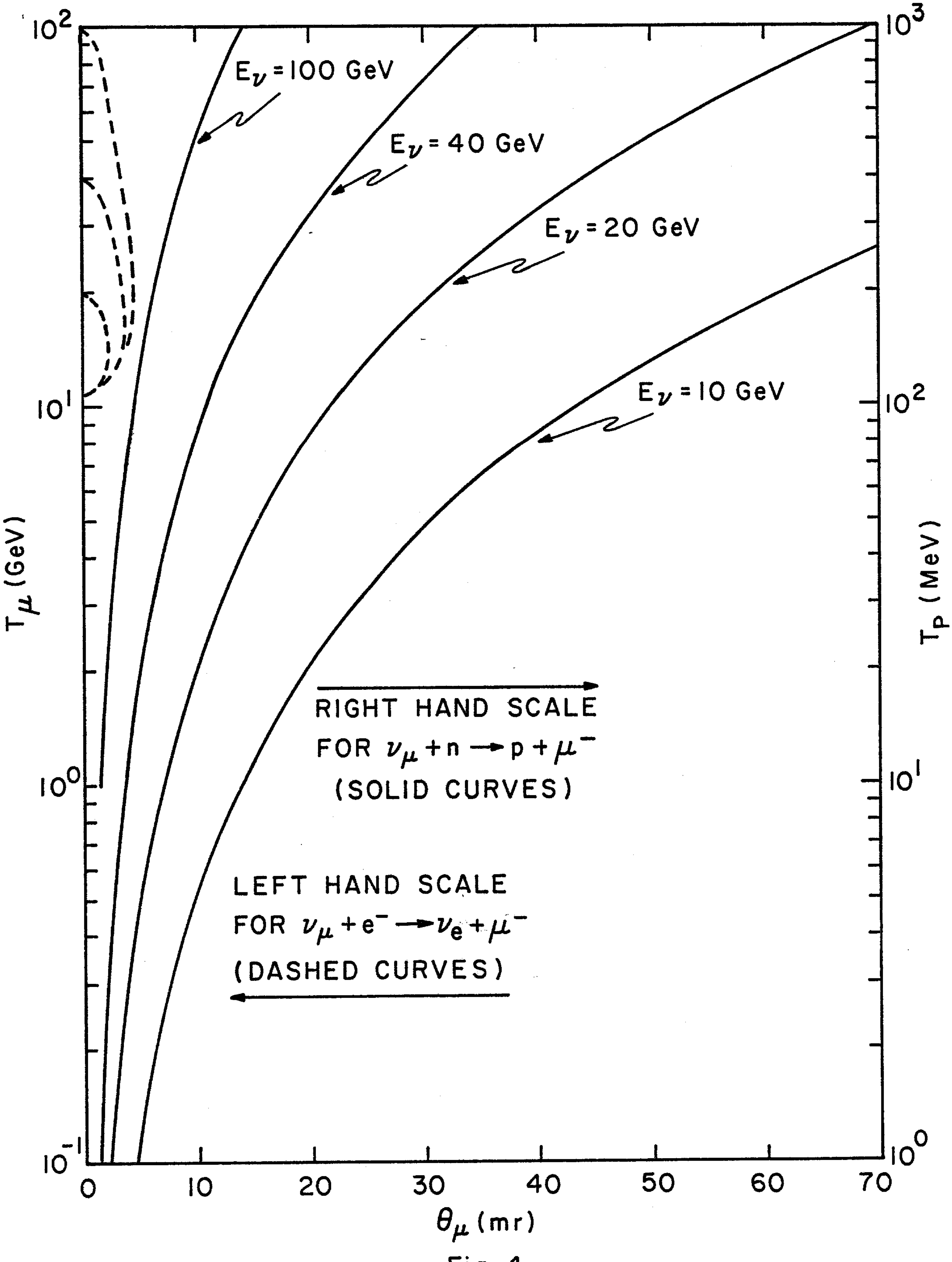
10^2
10^1
10^0
10^{-1}
10^3
10^2
10^1
10^0
0
10
20
30
40
50
60
70
T_μ (GeV)
T_P (MeV)
θ_μ (mr)
$E_\nu = 100$ GeV
$E_\nu = 40$ GeV
$E_\nu = 20$ GeV
$E_\nu = 10$ GeV
RIGHT HAND SCALE
FOR $\nu_\mu + n \rightarrow p + \mu^-$
(SOLID CURVES)
LEFT HAND SCALE
FOR $\nu_\mu + e^- \rightarrow \nu_e + \mu^-$
(DASHED CURVES)

Fig. 4

The above discussions assume that the inverse beta reaction occurs on free neutrons. Because q^2 is small ($|q^2| \sim p_\perp^2$ in this region), and because neutrons are bound, one has to consider nuclear binding effects, e.g. Pauli exclusion. For simplicity, we use the Fermi gas model for the nucleus.

Pauli exclusion can be easily accounted for in the Fermi gas model. Consider nuclei with $Z = \frac{1}{2}A$, one finds that Pauli exclusion suppresses low q^2 events by the following factor,[23] $R(Q)$:

$$R(Q) = \frac{1}{2}\left[3\left(\frac{Q}{2p_F}\right) - \left(\frac{Q}{2p_F}\right)^3\right] \qquad Q < 2p_F$$

$$= 1 \qquad Q \geq 2p_F$$

where $$Q^2 = |q^2|\left(1 + \frac{|q^2|}{4m_p^2}\right)$$

$$p_F = 0.284\ m_p$$

For the region of $|q^2|$ up to $(60\ \mathrm{MeV}/c)^2$, the Pauli factor suppresses the inverse beta cross section by a factor of about 8.[24]

Transformation of the neutron in the nucleus to a proton, in this q^2 region, will result in a daughter nucleus which will be in the "allowed" spectrum of states. These states may or may not de-excite with the emission of a proton.

For neutrons in nuclei and for small q^2 it is clear therefore, that the electron traverse momentum ($p_\perp^2 \sim |q^2|$) and the "recoil proton energy" become <u>independent</u> variables. This situation is identical to the case in semi-leptonic deep inelastic scattering

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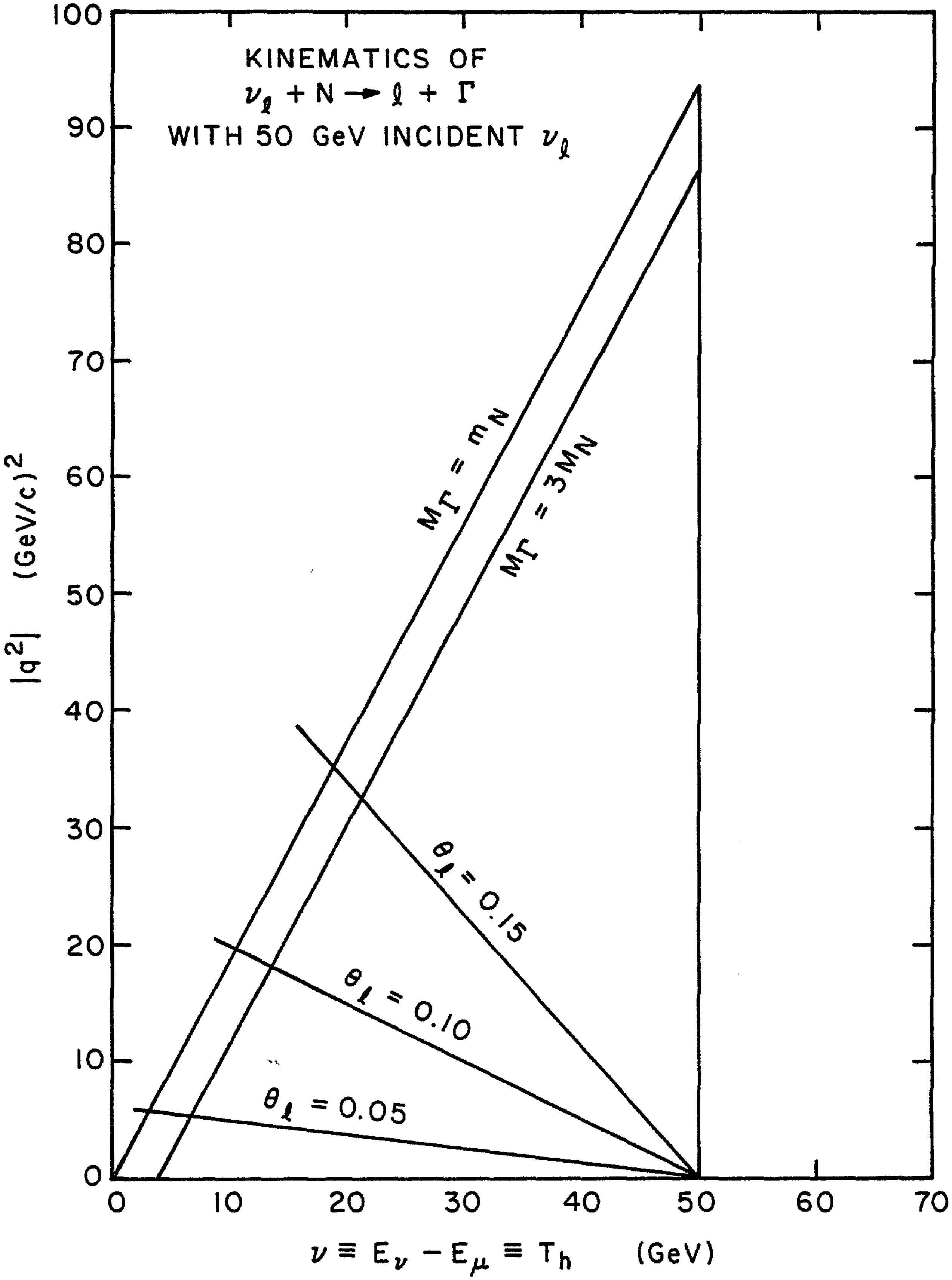
KINEMATICS OF
$\nu_\ell + N \rightarrow \ell + \Gamma$
WITH 50 GeV INCIDENT ν_ℓ
$M_\Gamma = m_N$
$M_\Gamma = 3M_N$
$\theta_\ell = 0.15$
$\theta_\ell = 0.10$
$\theta_\ell = 0.05$
$|q^2|$ $(GeV/c)^2$
$\nu \equiv E_\nu - E_\mu \equiv T_h$ (GeV)
0
10
20
30
40
50
60
70
80
90
100

Fig. 5

where the two independent variables frequently used are q^2 and ν (the hadron energy). In the case of nuclei, the manifestation of ν (the hadron energy) is nuclear excitation, i.e. "activity", at the interaction vertex. Nuclear de-excitation, i.e. additional "activity", which may be prompt, or delayed, also occurs at the interaction vertex. Thus both q^2 and ν may be used <u>independently</u> for background rejection.

We emphasize that by limiting the magnitude of q^2, one does not effectively limit the range of ν. However, by limiting ν, one also severely limits the magnitude of q^2. The kinematics of the usual semi-leptonic deep inelastic scattering reaction, see Fig. 5, clearly shows this. Alternatively by limiting ν, it is obvious that one gains additional discrimination <u>beyond</u> that possible by limiting q^2. Since it is difficult to estimate the discrimination capability achievable by limiting ν to such small values (there are nuclear effects, detection details, etc), we estimate discrimination factors conservatively by using estimates based upon limiting q^2 ($p_\perp^2$ since $|q^2| \sim p_\perp^2$ in this kinematic region).

The desirability of limiting "activity" at the interaction vertex is clear from the above. In practice, this method has been extensively applied mostly in bubble chamber work where the interaction vertex is "optically" visible. We propose to implement this method in a highly segmented, totally active, target/calorimeter such that the interaction vertex is "energetically" visible. Limiting energy deposition at the vertex provides a greater discrimination capability than limiting extraneous tracks within a bubble chamber. This occurs because track identification in a bubble chamber typically requires a particle with a range greater than about 1 mm. A 2 MeV proton has a typical range much less than 1 mm in a non gaseous medium. Therefore, such protons (and other heavy ionizing particles) would escape detection in bubble chambers.

To be specific, we will consider liquid argon (LA) in an ionization chamber as the active target. However, we note that the scintillation counter (SC) approach is also technically feasible and deserves serious consideration. The longitudinal segmentation (along the neutrino beam) allows location of the vertex within the leading layer. Analog information from the target layers, and adjacent layers, would limit excess energy deposition at the vertex.

To bypass the complexities associated with nuclear physics, we continue with considering inverse beta on free neutrons. The expectation is that the detector parameters will not be qualitatively different as long as this additional capability is included in the design.

A 2 MeV recoil proton from reaction (5) leaves almost at a right angle (88°) to the neutrino direction, and it has a range of 0.013 gm-cm^{-2} in Argon. Thus, such protons are contained in the leading layer and contribute ionization to this layer in addition to that from the electron. This excess energy is the key signature which we will use to reject the inverse beta background.

The thickness of liquid argon (LA) layers is determined both by the desired threshold for rejecting excess energy deposition in the vertex layer and by a desire to discriminate a single charged particle from multiple charged particles before initiation of an electromagnetic shower. Thus we choose the LA layer thickness to be 1 cm (1.40 $gm\text{-}cm^{-2}$).

Clearly, analog signals from such highly segmented layers can also be used to remove essentially all other backgrounds. For example, consider a single energetic gamma which converts in the LA. The gamma will generally pair produce. The large number of samplings in the thin LA layers, relative to the radiation length of LA (14.1 cm, 19.7 $gm\text{-}cm^{-2}$), will clearly identify the presence of a pair of charged particles even if the pair is highly asymmetric. Thus, discrimination against gammas can occur after conversion. It is clear, therefore, that one can constrain events to have only a single charged particle leaving the vertex.

The single charged particle, with muons as the exception, will cascade eventually in the LA. By itself, the LA does not distinguish effectively between electromagnetic and hadronic cascades (LA absorption length is 80.9 cm). Discrimination can be significantly improved by spacing a radiation length of Pb every radiation length of LA. The longitudinal development of the cascade, particularly the difference in the LA layers sandwiching the Pb, will label an electromagnetic cascade. The separation of electromagnetic and hadronic cascades can be further improved, particularly for hadronic cascades with an electromagnetic component, by measuring the fluctuation in the ionization of the cascade.[25 28]

The following section gives some details of a deterctor system which incorporates the above method to study ν_μ, e^- elastic scattering. The same detector will also have the capability of studying ν_μ, e^- inverse muon decay. The kinematics for this reaction, corresponding to that of Fig. 3 and 4 for ν, e elastic scattering, is shown in Fig. 6 and 7, respectively

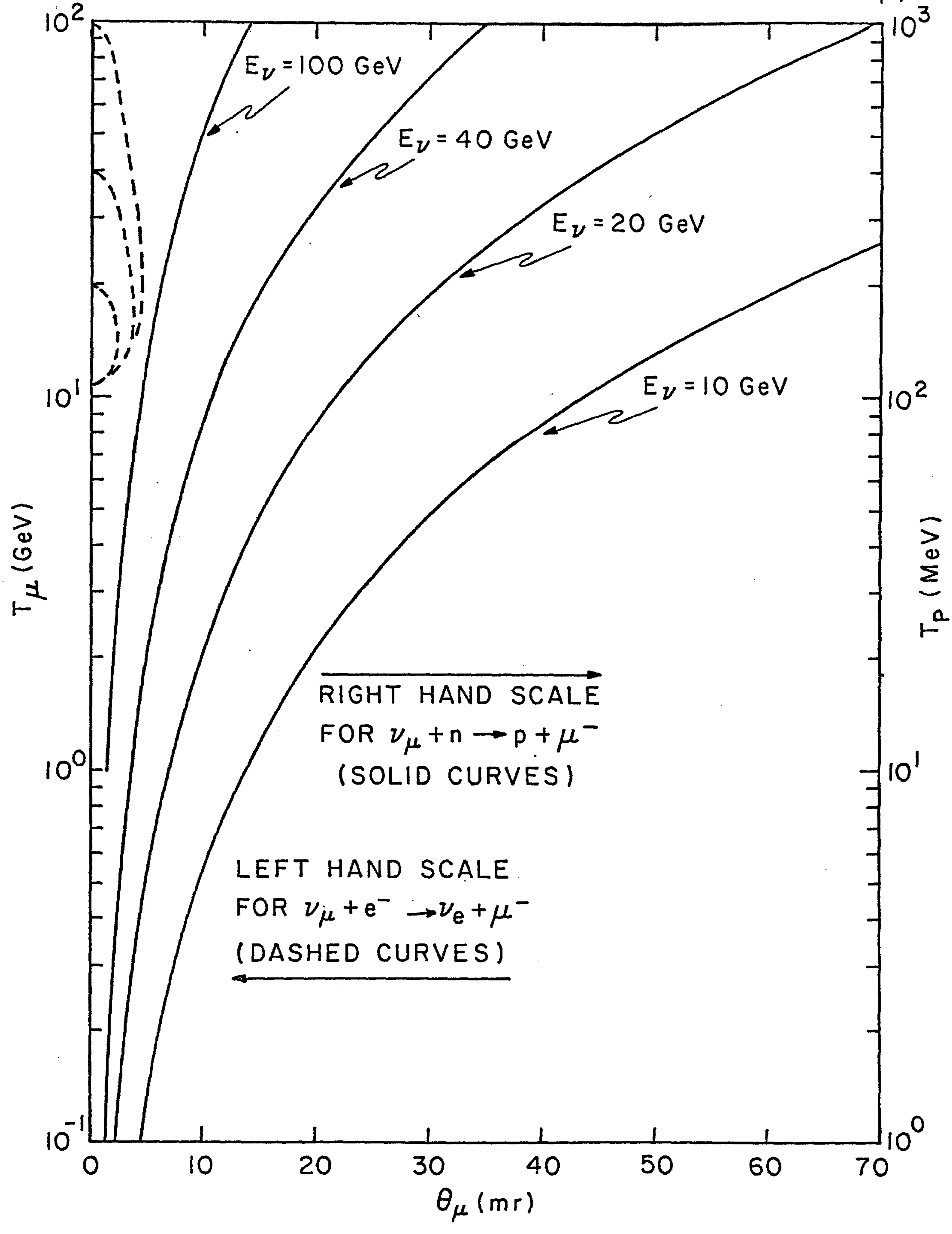
10^2
10^1
10^0
10^{-1}
10^3
10^2
10^1
10^0
0
10
20
30
40
50
60
70
E_ν = 100 GeV
E_ν = 40 GeV
E_ν = 20 GeV
E_ν = 10 GeV
T_μ (GeV)
T_p (MeV)
RIGHT HAND SCALE
FOR $\nu_\mu + n \rightarrow p + \mu^-$
(SOLID CURVES)
LEFT HAND SCALE
FOR $\nu_\mu + e^- \rightarrow \nu_e + \mu^-$
(DASHED CURVES)
θ_μ (mr)

Fig. 6

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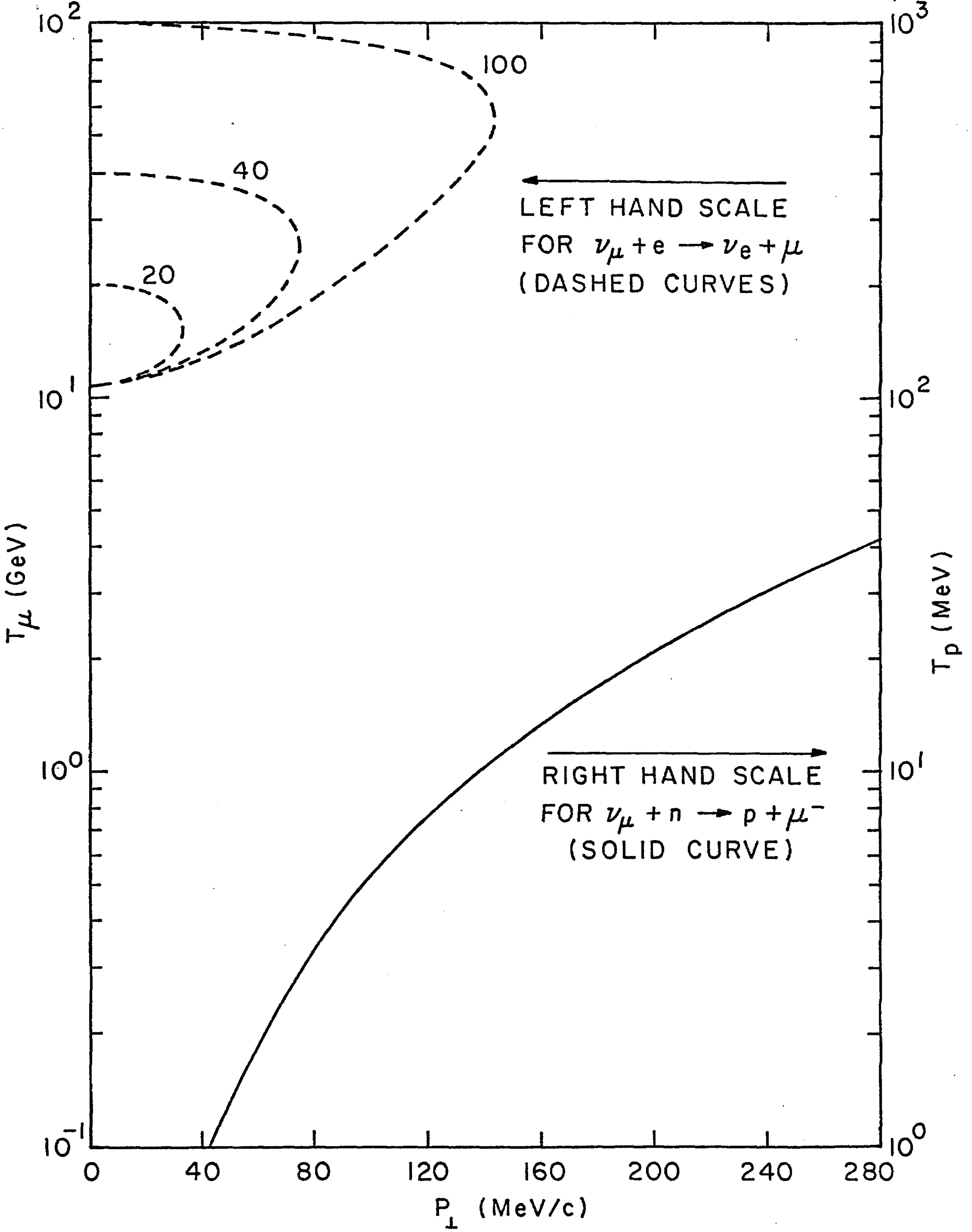
100
40
20
LEFT HAND SCALE
FOR $\nu_\mu + e \rightarrow \nu_e + \mu$
(DASHED CURVES)
RIGHT HAND SCALE
FOR $\nu_\mu + n \rightarrow p + \mu^-$
(SOLID CURVE)
T_μ (GeV)
T_p (MeV)
10^2
10^1
10^0
10^{-1}
10^3
10^2
10^1
10^0
0
40
80
120
160
200
240
280
$P_\perp$ (MeV/c)

Fig. 7

V. Detector System

The considerations in the preceeding section indicates that the detector system should have the following components.

1) a highly segmented, independently sampled, totally live target consisting of roughly a thousand planes of liquid argon.

2) layers of one radiation length Pb in the liquid argon to separate electromagnetic and hadronic cascades.

3) instrumentation in the liquid argon to determine shower direction.

4) a muon spectrometer for muon identification and momentum measurement.

A schematic of such a detector system was shown in Fig. 2. It contains:

1) a liquid argon target/calorimeter

2) a hadron calorimeter

3) a muon spectrometer.

The target/calorimeter is modular in concept. A schematic of one of the modules is shown in Fig. 8. Each module contains: 15 liquid argon layers of 1 cm each; and a 1 radiation length layer of Pb. The prototype target/calorimeter for stage I uses 15 modules while the stage II detector requires 75 modules. These modules, except for the one radiation length of Pb, contain essentially no inert material. i.e. the ionization chamber electrodes are of low mass (alternating wires and wire screens).

Each module would be instrumented to measure a redundent set of transverse co-ordinates in addition to the required analog sampling of each layer. With a hexagonal structure, each module

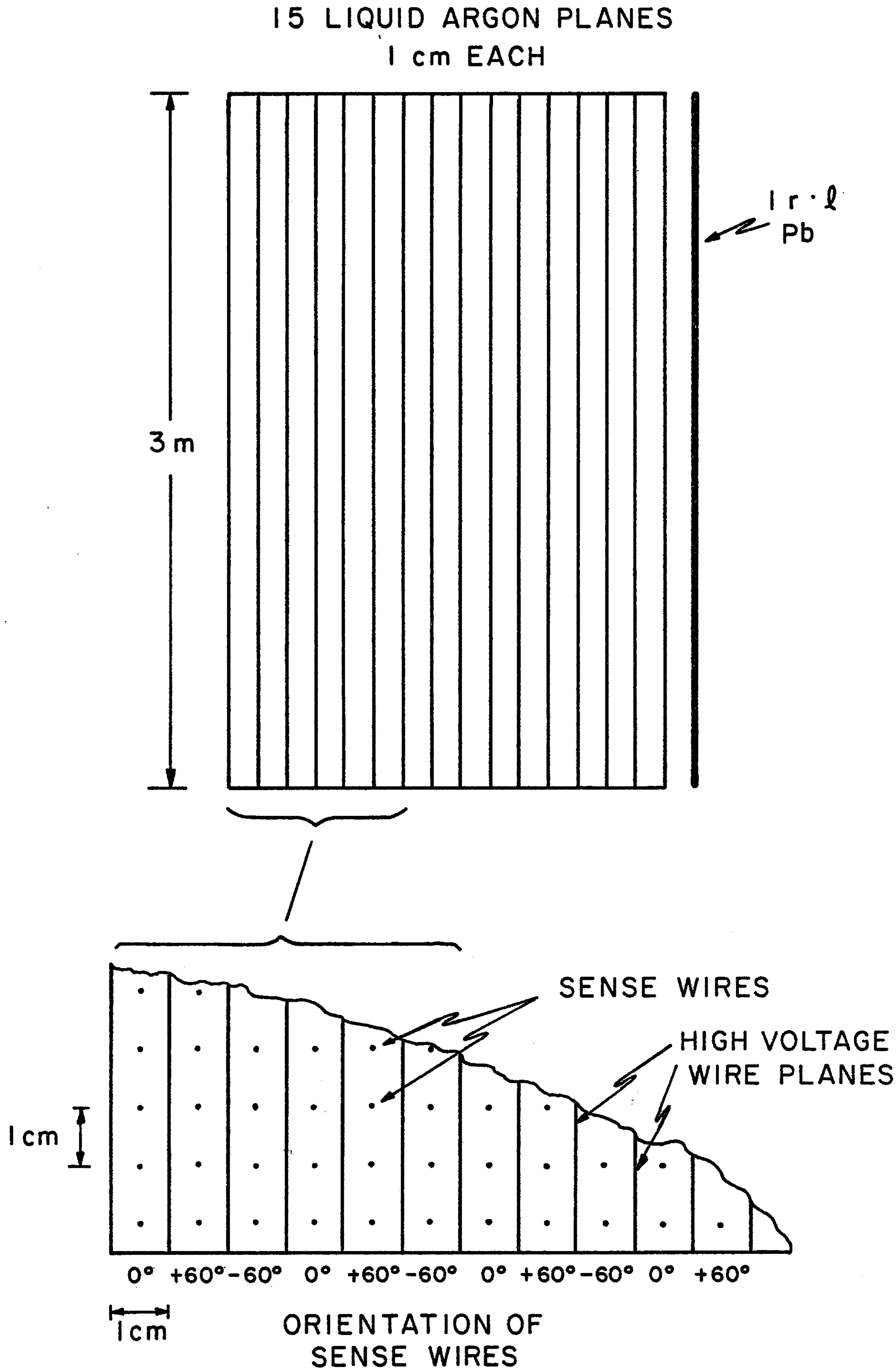
15 LIQUID ARGON PLANES
1 cm EACH
3 m
1 r·ℓ
Pb
SENSE WIRES
HIGH VOLTAGE
WIRE PLANES
1 cm
0° +60° -60° 0° +60° -60° 0° +60° -60° 0° +60°
1 cm
ORIENTATION OF
SENSE WIRES

Fig. 8

will record three transverse co-ordinates (rotated relative to each other by 60°). The measurement of transverse co-ordinates significantly increases the number of independent analog channels. However, due to the simplicity of neutrino electron reactions and the lateral confinement of the electromagnetic shower to within a diameter of about 30 cm in liquid argon (with the Pb layers, the confinement diameter is roughly a factor of 2 smaller), one can reduce the total number of such channels by more than an order of magnitude via multiplexing. An estimate shows that 87 (25 x 3 + 12) analog channels would be sufficient for reading out the 4,500 sense wires per module. Thus the prototype (full scale) target/calorimeter would require 1,305 (6,525) analog channels.

The hadron calorimeter, and muon spectrometer follow standard designs. In particular, the hadron calorimeter and muon spectrometer required here exist as components of the Caltech/Fermilab neutrino detector system, and may be used without modification. Furthermore, as shown in Fig. 2, one sees that the Caltech/Fermilab detector remains essentially intact and unaffected by the placement of the new target/calorimeter in a frontal extension of Lab E. This is possible *since recoil angles in neutrino electron reactions are* small. This configuration allows great flexibility both during installation and during data taking.

The major new component in this detector system is the liquid argon target/calorimeter. Even though the technique of using liquid argon ionization chambers is relatively new,[25,26,27] it is currently being applied on a significant scale both at the ISR (CERN),[28] and at SPEAR (SLAC).[29] It is also being studied for possible application at PEP(SLAC).[30,31] The mass scales of these liquid argon calorimeters are 210 tons and 72 tons, for the ISR and SPEAR respectively, and 200 and 400 tons for PEP. The number of analog channels used are 1,800 and 4,000 for the ISR and SPEAR calorimeters; and 12,500 and 2,100 for PEP respectively. It is clear from the above numbers that the liquid argon calorimeters at colliding beam accelerators are already at the mass scale, and are using approximately the number of analog channels, we are proposing. Furthermore, the physical constraints for liquid argon calorimeters at colliding beam accelerators are much more severe than our proposed neutrino target/calorimeter. It is evident from the above that massive liquid argon calorimeters are being applied at a rapid pace in high energy experiments.

VI. Event Rates

The Fermilab ν_μ spectrum with the horn focusing system is shown in Fig. 9. We calculate the number of events under the following assumptions:

1) 1 Coulomb of 400 GeV protons

   i.e. a) 10^{13} protons/pulse

   b) 600 pulses/hour

   c) 10^3 hours

2) Wide band horn focused ν_μ beam

3) 80 ton fiducial target

   i.e. 2.4×10^{31} electrons.

For ν_μ, e^- elastic scattering, we take the minimum cross section from the Weinberg/Salam-Ward model, i.e. $x = \sin^2 \theta_W = 0.375$, which is 10^{-42} E_ν(GeV) cm^2. For ν_μ, e^- inverse muon decay, the cross section is uniquely determined by V-A theory. It is

$$\sigma = \sigma_o E_\nu \left(1 - \frac{E_o}{E_\nu}\right)^2 \tag{7}$$

where $E_o = m_\mu^2/2m_e = 10.92$ GeV

$\sigma_o = 16.2 \times 10^{-42}$ cm^2/GeV.

Deviation of the ratio $|g_A/g_V|$ from 1 in muon decay affects this cross section to lowest order, i.e. the cross section is uncertain to 25%.

The number of events, calculated with the above assumptions, is 240 for ν_μ, e^- elastic scattering, and 1260 for ν_μ, e^- inverse muon decay. The constraint, limiting excess energy deposition at the vertex, does not reduce the number of events for either reaction. A second constraint $p_\perp^2 \leqslant 0.015$ (GeV/c)^2 reduces the number of events by 5%, to 225 and 1200 respectively.

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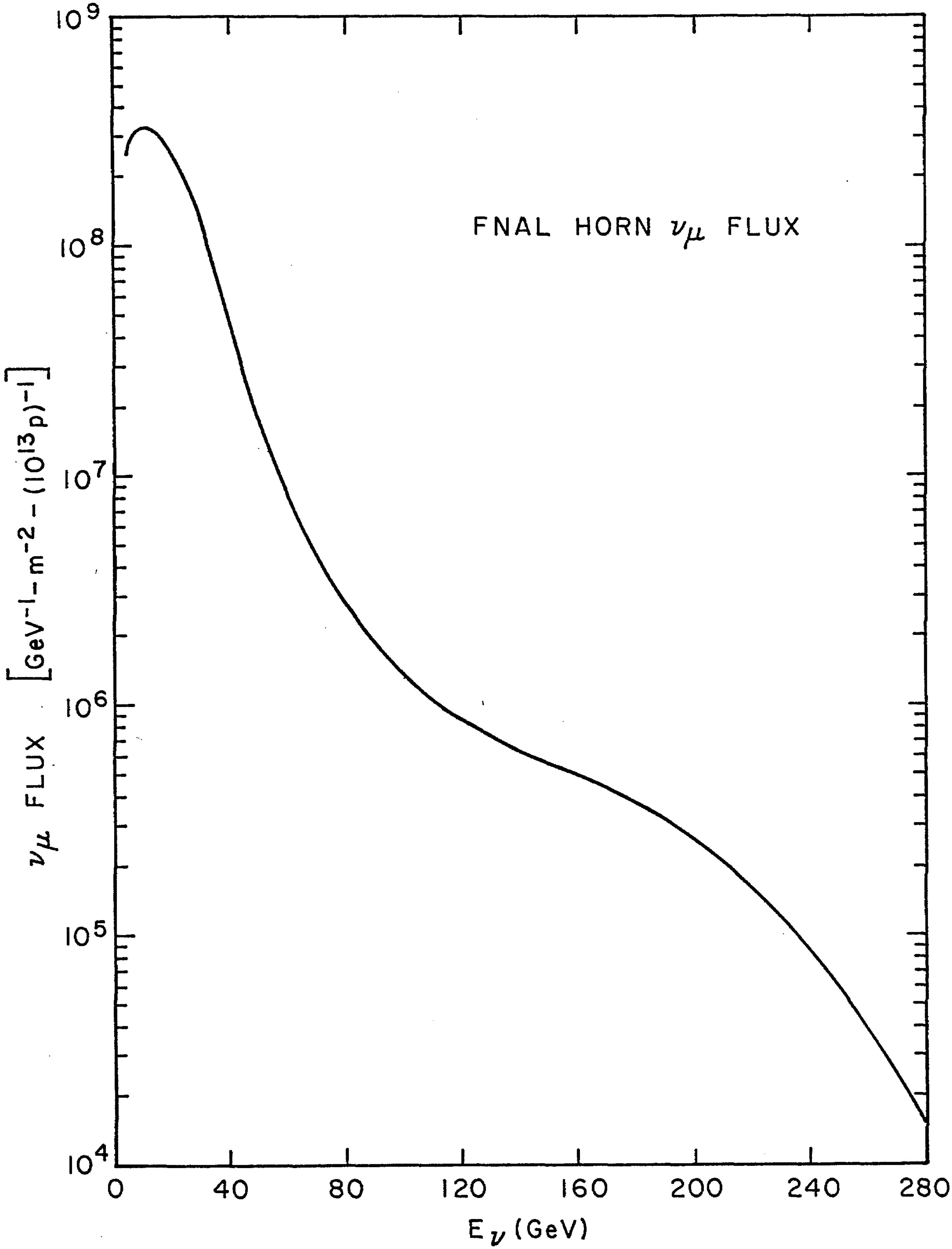

FNAL HORN ν_μ FLUX
ν_μ FLUX $\left[GeV^{-1}-m^{-2}-(10^{13}p)^{-1}\right]$
10^9
10^8
10^7
10^6
10^5
10^4
0
40
80
120
160
200
240
280
E_ν (GeV)

Fig. 9

The ν_μ, e^- elastic scattering recoil electron differential spectrum, integrated over the incident neutrino spectrum and using the above $p_\perp^2$ cut, is shown in Fig. 10. The corresponding spectra with x = 0.25 and 0.50 are also shown. This Figure clearly shows the necessity of using a low (electron) energy threshold. e.g. the imposition of a 2 GeV energy threshold reduces the number of events to 175 (255, and 220 for x = 0.25 and 0.50, respectively).

The ν_μ, e^- inverse muon decay muon differential spectrum (due to the high threshold energy), starts at 11 GeV. This indicates that relatively few additional events would be lost beyond those removed by the $p_\perp^2$ cut.

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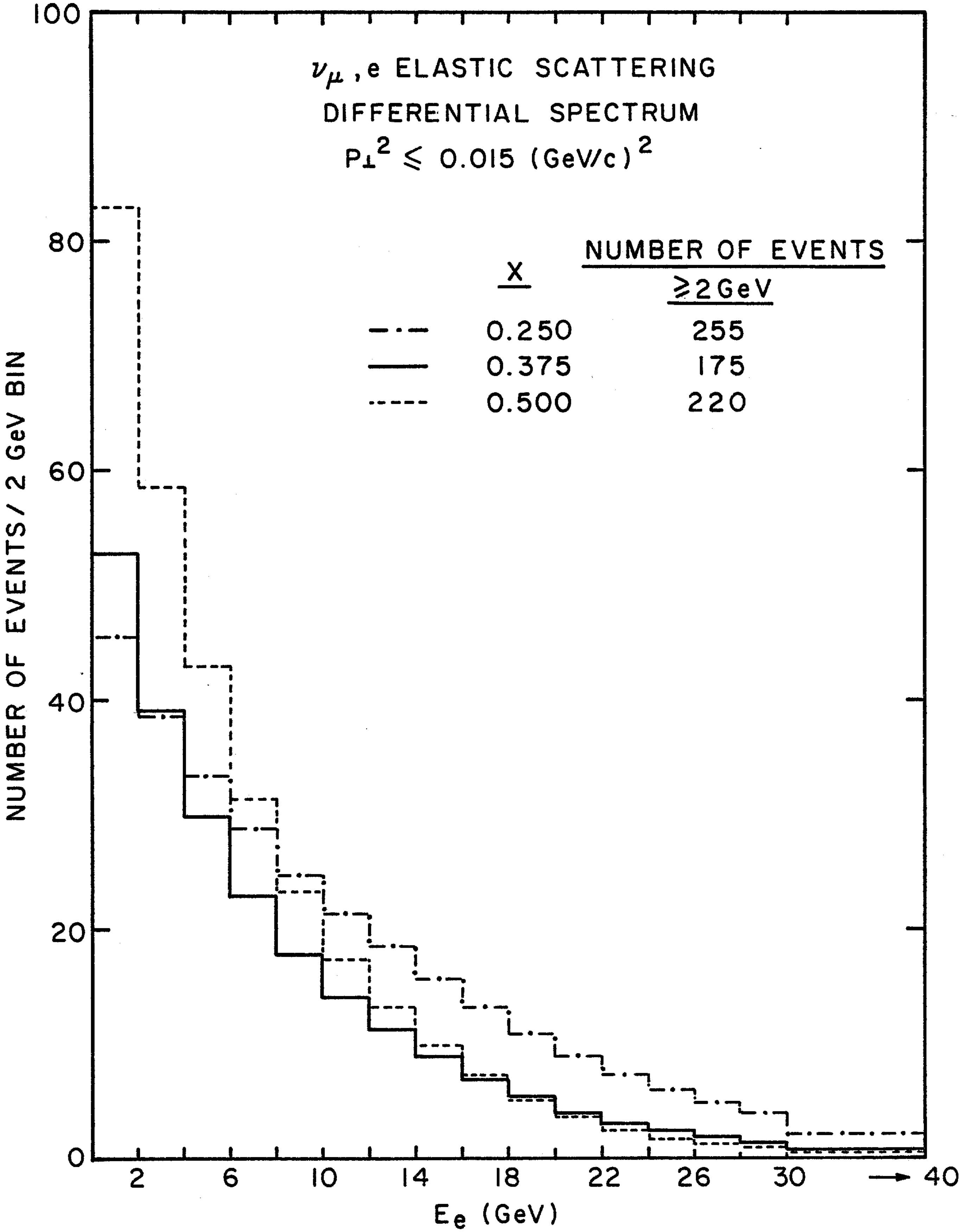

Fig. 10

VII. Background Rates

A) Backgrounds for $\nu_\mu e \to \nu_\mu e$

As discussed earlier, a background to ν_μ, e^- elastic scattering is inverse neutron beta decay. We calculate the number of events with the previous assumptions, and that the ν_μ beam has a 1% ν_e contamination with the same spectral shape. Furthermore, we take the inverse beta cross section to be a constant at $10^{-38}cm^2$.(32) The calculated number of such events is 1100.

Discrimination against this reaction was extensively discussed. Because the target neutrons are in nuclei, i.e. ^{40}A, one should include Pauli exclusion effects. Imposing a transverse momentum cut on the electron at 130 MeV/c, we remove 94% of the inverse beta events, i.e. 70 such events are left if the neutrons are free. The vertex energy criteria of 2 MeV excess energy deposition will contribute at least an additional factor of 5 discrimination against this background reaction (estimated by using a 60 MeV/c cut on transverse momentum), i.e. $\leqslant$ 14 events would remain. For bound neutrons, one would have $\leqslant$ 2 events if one includes the Pauli suppression. The number of these residual events can be estimated from the observed transverse momentum distribution, and/or the excess vertex energy spectrum, and subtracted from ν_μ, e^- elastic scattering candidates.

Single pion production by the neutral current interaction with ν_μ is assumed to have a constant cross section at 2×10^{-39} cm^2/nucleon and to be dominated by Δ production.(33,34) This gives a total of 44,000 events produced.

Due to weak form factors, the energy spectrum of the recoil hadrons drops rapidly at energies $\geqslant$ 1 GeV. We estimate as follows: with $|q^2| \sim 3m_p^2$, the energy of the forward going π from Δ decay is 1 GeV (the total hadronic kinetic energy is $\sim$ 1.8 GeV). Thus a relatively low energy cut will remove events with $|q^2|$ up to $\sim 3\ m_p^2$. Assuming the usual quadratic form factor, this gives the result that events with $|q^2| \geqslant 3\ m_p^2$ is less than ~ 2% of the total i.e. ~ 890 events. This occurs before the vertex energy criteria, the single charged particle criteria, the angular criteria, and electromagnetic shower criteria are used. The large q^2 in these events generally breaks up the target nucleus. Thus these additional criteria are expected to provide, in all, a discrimination much larger than 10^2, and this particular background reaction would appear to be reasonably in hand.

B) <u>Background for $\nu_\mu e^- \rightarrow \mu^- \nu_e$</u>

The major background for ν_μ, e^- inverse muon decay is the quasi-elastic inverse beta decay reaction which we intend to use for normalization, i.e.

$$\nu_\mu\ n \rightarrow p\ \mu^- . \qquad (8)$$

The number of events from this reaction is 110,000. A transverse momentum cut of 130 MeV/c would remove 94% of these events, and leave a total of 6600 events. The vertex energy criteria contributes at least an additional factor of 5, so that 1300 events are left. Pauli suppression of these low q^2 events indicates that there will actually be 160 events, of which 100 have muons with energy above 10.92 GeV. Thus we see that the background from reaction (8) is much less than the inverse muon decay signal. Furthermore the number of these residual events can again be estimated from the observed transverse momentum distribution, and/or the excess vertex energy spectrum, and subtracted from ν_μ, e^- inverse muon decay candidates.

VIII. Summary

We are proposing to build a new counter neutrino detector system which will require a new target/calorimeter section and which will make effective use of the Caltech/Fermilab detector. This new detector system, because of its sensitivity, could be used to search for new phenomena down to a level 10^{-3}-10^{-4} that of the usual charged current reaction. The first use of this detector would be the study of neutrino electron reactions at Fermilab. The key feature in this detector system is its sensitivity to very low ν ($= E_\nu - E_\ell = T_h$), and also very low q^2. In particular because the target is highly segmented, individually sampled, and totally live, it can be sensitive to excess hadron energy deposition at the vertex of a few MeV. In particular this capability allows rejection of very low ν, and very low q^2 events from neutrino nucleon reactions. This capability is sufficient for the study of ν_μ, e^- elastic scattering, and ν_μ, e^- inverse muon decay.

Future experiments for this detector, possibly with the energy doubler, include the remaining neutrino electron reactions i.e.

i) a study of $\bar{\nu}_\mu, e^-$ elastic scattering

ii) a test of the multiplicative lepton number conservation law via a search for $\bar{\nu}_\mu e^- \to \bar{\nu}_e \mu^-$, and

iii) a study of $\nu_e(\bar{\nu}_e), e^-$ elastic scattering,

These studies would require, respectively, the wide band $\bar{\nu}_\mu$ beam, and the proposed K° decay neutrino beam.

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